ARMv8.3 Pointer Authentication

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Background

- Memory protections are commonly deployed today
  ... largely prevents code injection
- Focus has shifted to code reuse attacks
  ... e.g. ROP, JOP
- Various mitigations today
  ... e.g. ASLR, execute-only memory, CFI, canaries, pointer mangling, shadow stacks
  ... not as widely deployed
  ... can be difficult to integrate
  ... can have non-trivial performance / code size impact
  ... can inhibit debugging

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Pointer authentication

- Optional ARMv8.3-A extension
- Detects illicit modification of pointers (and data structures)
  ... can be used to catch ROP, etc
  ... simple to integrate
  ... with minimal code size / performance impact
- Backwards compatible subset
  ... binaries using some features can run on any ARMv8-A CPU (without protection)
  ... so distributions only need one set of binaries

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ROP protection example

```
paciasp
stp fp, lr, [sp, #-FRAME_SIZE]!
mov fp, sp

< function body >

ldp fp, lr, [sp], #FRAME_SIZE
autiasp
ret
```


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Theory

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Pointer authentication basics

- New instructions to sign and authenticate pointers
  - ... against a user-chosen (dynamic) context
  - ... e.g. return address is valid for a given stackframe
  - ... architecture provides mechanism, not policy
- Uses a Pointer Authentication Code (PAC)
  - ... authentication metadata stored within pointer
  - ... so no additional space required

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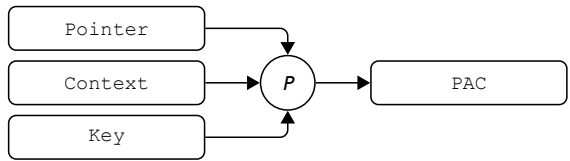
Pointer Authentication Codes

- Each PAC is derived from:
  - A pointer value
  - A 64-bit context value
  - A 128-bit secret key
- PAC algorithm *P* can be:
  - QARMA[1]
  - `IMPLEMENTATION DEFINED`
- Instructions hide the algorithm details



[1] https://eprint.iacr.org/2016/444.pdf

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Keys

- Secret 128-bit value
  ... inhibit prediction / forging of PACs
- Held in system registers
  ... can be used, but not read/written at EL0 (userspace)
  ... limited risk of disclosure / modification
- Several keys:
  - `APIAKey`, `APIBKey` (instruction pointers)
  - `APDAKey`, `APDBKey` (data pointers)
  - `APGAKey` (data)

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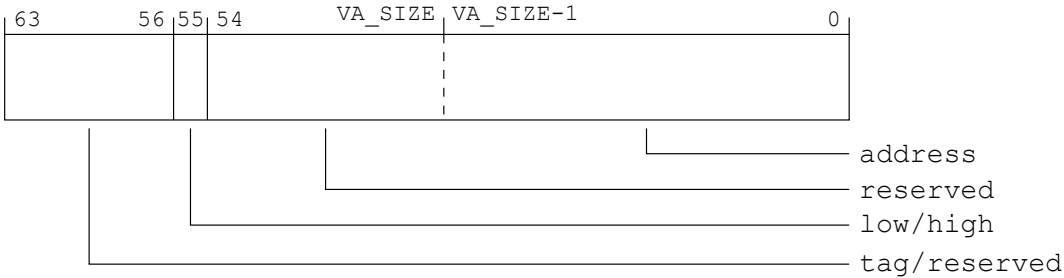
Pointers in AArch64



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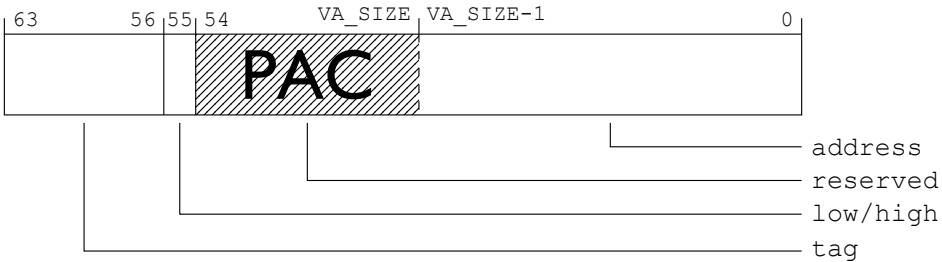
Pointers in AArch64 (with authentication)

- PAC embedded in reserved pointer bits
  ... e.g. 7 bits with 48-bit VA with tagging
  ... leaving remaining bits intact



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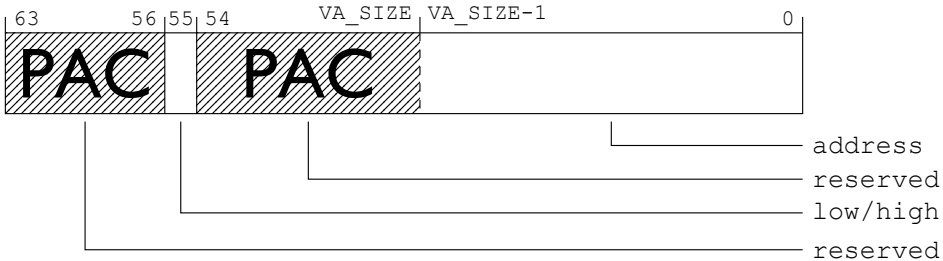
Pointers in AArch64 (with authentication)

- PAC embedded in reserved pointer bits
  - ... e.g. 15 bits with 48-bit VA without tagging
  - ... leaving remaining bits intact



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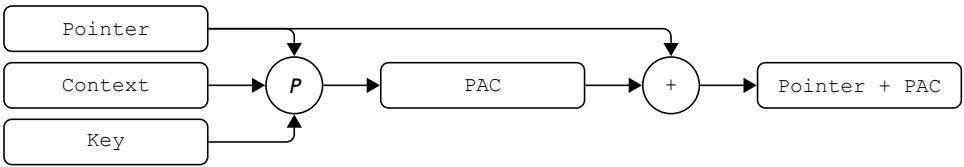
Operations: sign

- `PAC*` instructions sign pointers with PACs
- Result is not a usable pointer



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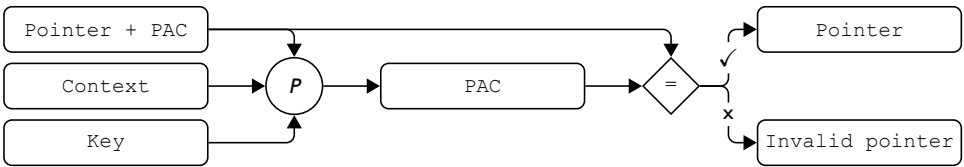
Operations: authenticate

- `AUT*` instructions authenticate PACs
- If PAC matches, result is the original pointer
- If PAC doesn't match, result is an invalid pointer → faults upon use



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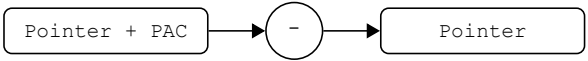
Operations: strip

- `XPAC*` instructions strip PACs
- Result is the original pointer
- No authentication is performed



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Usage

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ROP vulnerable code

```
stp fp, lr, [sp, #-FRAME_SIZE]!
mov fp, sp

< function body >

ldp fp, lr, [sp], #FRAME_SIZE

ret lr
```


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ROP protection

```
pacia lr, sp
stp fp, lr, [sp, #-FRAME_SIZE]!
mov fp, sp

< function body >

ldp fp, lr, [sp], #FRAME_SIZE
autia lr, sp
ret lr
```


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ROP protection (backwards compatible)

```
paciasp
stp fp, lr, [sp, #-FRAME_SIZE]!
mov fp, sp

< function body >

ldp fp, lr, [sp], #FRAME_SIZE
autiasp
ret lr
```


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Other uses

- Many potential uses / contexts:
  - locally-scoped pointers / stackframe
  - PLTs / PLT address (dynamic link time)
  - opaque pointers / logical type, owner
- Architecture provides mechanism, not policy
- needs careful consideration of reuse attacks
  - Need to avoid signing gadgets
  - May require multiple keys for distinct purposes

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Software support

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Linux Kernel

- RFCs[2][3] posted
- Enables userspace use
  - ... per-process `APIAKey` initialized at exec() time
  - ... context-switched by kernel
  - ... retained across fork()
- Ptrace interface to find PAC bits (but not keys)
- Basic KVM support
- No kernelspace pointer authentication (yet)

[2] https://lkml.kernel.org/r/1491232765-32501-1-git-send-email-mark.rutland@arm.com

[3] https://lkml.kernel.org/r/1500480092-28480-1-git-send-email-mark.rutland@arm.com

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Toolchain

- Upstream GCC 7 supports `-msign-return-address=[non-leaf | all]`
  ... uses APIAKey, backwards-compatible instructions (by default)
- GDB support pending kernel ptrace patches
- Thanks to Jiong Wang, Yao Qi

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Questions?

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